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ADP013505

TITLE: Detection and Severity Assessment of Faults in Gear Boxes from Stress Wave Capture and Analysis

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TITLE: New Frontiers in Integrated Diagnostics and Prognostics. Proceedings of the 55th Meeting of the Society for Machinery Failure Prevention Technology. Virginia Beach, Virginia, April 2 - 5, 2001

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DETECTION AND SEVERITY ASSESSMENT OF FAULTS IN GEAR BOXES FROM STRESS WAVE CAPTURE AND ANALYSIS

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Abstract: Many faults in gearboxes are accompanied by the emission of stress waves that disperse away from the initiation site at the speed of sound in metal. The wave propagation introduce a propagating ripple on the surface which will introduce a response, output, in a sensor sensing absolute motion such as an accelerometer. For an accelerometer at a fixed location, the wave propagation will be a reasonable short-term transient event lasting on the order of fractional to several milliseconds. The duration of the event will be dependent on (1) type of event e.g., stress waves from impacting will last longer than stress waves accompanying the release of residual stress buildup through fatigue cracking, (2) relative location of the sensor (accelerometer) to the initiation site, and (3) severity of the fault responsible for the stress wave emission.

For a healthy smooth running machine (gearbox), there generally will be no stress waves present. Therefore their presence is indicative of a defect which generates stress waves. Some common defects which generate stress waves are pitting in the races causing the rollers to impact, fatigue cracking in bearing raceways or gear teeth (generally at root), scuffing or scoring on gear teeth, cracked gear teeth, and others. The challenge becomes one of detecting and quantifying relative to energy and repetition rate (or lack thereof) the stress wave activity. This leads to the identification of certain faults and, with experience, their severity.

The methodology employed by CSI per the capture and analysis of stress waves are to collect a block of data consisting of peak values (in g's) which occur within discrete sequential equal time intervals determined by the resolution sufficient to identify faults. The number of time intervals over which peak values are collected are consistent with that needed to invoke spectral analysis for the desired resolution and spectral band width.

The magnitude of the stress wave packets is identified in the discrete time data block containing peak values. The presence of periodicity is identified in the spectral (frequency) domain. An alternative to spectral analysis for the identification of periodicity is auto-correlation analysis.

To illustrate this peak value (PeakVue™) analysis for fault detection and severity assessment in gearboxes, several case studies are presented. The specific faults demonstrated are bearing faults, cracked gear teeth, unstable driver speed, and torsional vibration. It will be demonstrated that the PeakVue methodology is a very beneficial tool for monitoring gearboxes.

Introduction: Many mechanical faults within industrial rotating machinery manifest themselves through modal excitation (vibration) and stress wave initiation. Modal excitation can be detected using sensors which detect absolute or relative motion. A common sensor employed for detection of absolute motion is the accelerometer. The

The method employed by CSI for stress wave analysis avoids the use of a low pass filter completely. This is accomplished by separating, as much as possibly, the stress wave activity (the short term transient activity) from the continuous activity by routing the signal from the sensor through a high pass filter set consistent with possible fault frequencies within the machine. The resultant time signal is converted into a digital signal at constant time increments for further analysis. The digital value recorded over each time increment is not the signal value at a specific time, but instead is the absolute maximum (peak) value observed over each discrete time interval. The resultant digital representations are peak values, which occurred over each time increment.

The analysis of the peak value (PeakVue™) waveform is basically (1) the identification of any periodic activity occurring at rates consistent with possible fault frequencies and (2) severity of assessment based on the level (peak value) of the stress wave activity. The presence of periodic activity is identified through spectral analysis of the digital block of data consisting of the sequential peak values. Severity level is extracted from observed peak values compared with similar faults and/or trending of the peak values.

3. Case Studies

3.1 Introduction: The case studies chosen for presentation will demonstrate an outer race and an inner race defect in separate pinion stand gear boxes. Sufficient data was available to demonstrate the importance of trending for the inner race defect case. The third case demonstrates severe cracked teeth in a Precision Tension Bridle gearbox. The fourth case is from an extruder gearbox being driven by a DC motor with speed variation. The fifth case was selected to demonstrate a torsional resonance problem present in a large crusher gearbox.

3.2 Outer Race Defect in Pinion Stand Gearbox: This pinion stand gearbox was included in the scheduled monthly condition monitoring program employing vibration analysis. The traditional vibration monitoring showed no indication of a bearing fault. In July 1997, the PeakVue methodology was introduced into the monitoring program.

It was obvious from the PeakVue data there was an outer race defect on the inlet shaft. The peak g readings were 18 g's (the normal vibration readings were showing 1.5 g's with no indication of a problem). The peak g readings in PeakVue continued to trend up (got to 38 g's in mid Sept. 1997) and then started a downward trend (14 g's in early October). The bearing was then replaced the peak g-levels on the replacement bearing was less than 1-g.

The normal vibration spectra and acceleration time waveform for data acquired on September 15 1997 are presented in Figure 1. There is some indication of a possible outer race problem but not conclusive.

The data from the PeakVue methodology acquired on the same date are presented in a Figure 2. The peak absolute g-levels are up to 38 g's with a recurring rate consistent with the outer race defect frequency. The bearing was replaced in early October 1997. A picture of the defective bearing is presented in Figure 3. The defects in the outer race are apparent.

analysis of the modal motion relative to the machine health is referred to as vibration analysis. The methodology employed in vibration analysis consists of:

1. Capture (digitally) of a time waveform from a sensor for a specified time period. The signal is first passed through a high order low pass filter prior to digitalization. The purpose of the low pass filter is to remove all frequency content which exceeds the Ngquist frequency (one half the sampling rate).
2. Transform the modified discrete time waveform into the frequency domain employing FFT methodologies.
3. Look for excessive activity compared to other similar machinery or previous history at discrete know fault frequencies.

The implicit assumption in vibration analysis is the signal being analyzed is stationary equilibrium. The spectral values are average values, which are appropriate for stationary (continuous) conditions.

Stress waves in metal accompany actions such as impacting, fatigue cracking, scuffing (scoring) abrasive wear, etc. Stress wave emissions are short term, lasting several microseconds to a few milliseconds, transient events which propagate away from the initiation site as bending (s) and longitudinal (p) waves at the speed of sound in metal. The s waves introduce a ripple on the surface which will excite an absolute motion sensor such as an accelerometer. The detection and classification of these stress wave packets provide an important diagnostic tool for (a) detecting certain classes of problems and (b) severity assessment.

In the next section, a brief discussion of the methodology employed by CSI for stress wave capture and analysis will be presented. The next section will present several case studies showing the detection and severity assessment for faults commonly experienced in gearboxes. The last section will be a summary and conclusion section.

2. Capture and Analysis Methodology for Stress Wave Activity: Stress waves are generated when impacting, scuffing (scoring), fatigue cracking, abrasive wear, etc. are present The duration of an individual event will range form fractional to several milliseconds. The rate at which individual events occur within rotating machinery generally are periodic consistent with the fault, e.g., a pitted area in the outer race will cause impacting at the outer race fault frequency.

The sensor generally employed for the detection of stress waves is the accelerometer. Since the signal is a short-term event relative to the repetition rate, the methodology employed for the detection of the events preferable should avoid any averaging. This is because there can be a large variation in repetition rate and hence the duty cycle will introduce large variations in average values independent of the severity level of the fault. Averaging negates the ability to perform severity level analysis based on trending and relative comparisons.

When executing vibration spectral analysis, the general procedure is to route the sensor analog signal through signal conditioning, which includes a low pass filter (anti-aliasing) immediately prior to conversion into a digital signal with discrete values at a constant sampling rate. The low pass filter is an averaging process; hence any short term events are averaged over the averaging time associated with the anti-analyzing filter.

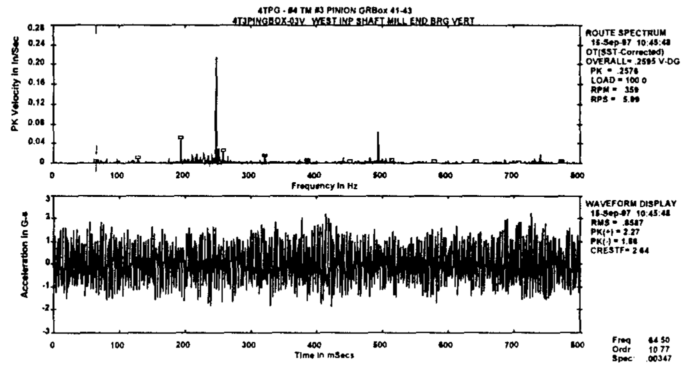

Figure 1. Vibration velocity spectra and acceleration time waveform on pinion stand gearbox on September 15, 1997.

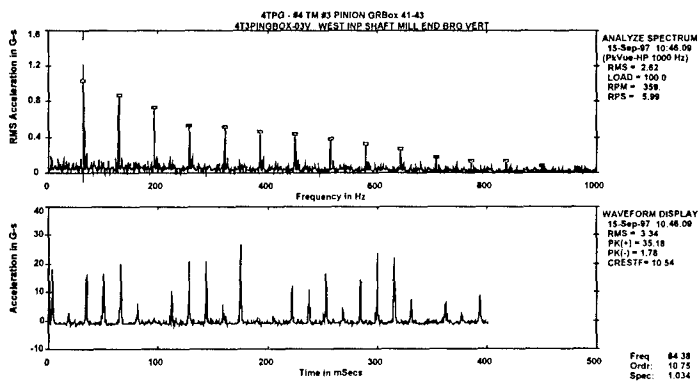

Figure 2. PeakVue spectra and time waveform on Pinion stand gearbox (same as Fig. 1.)

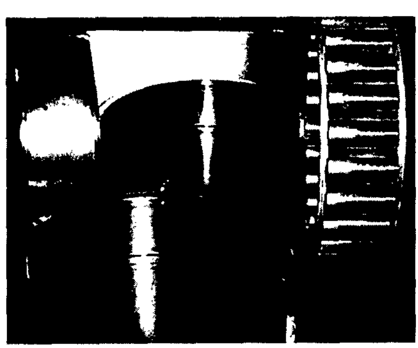

Figure 3. Defective bearing taken from the pinion gearbox of Figs. 1 and 2.

3.3 Inner Race Defect in Finish Mill Pinion Stand Gearbox: This pinion stand gearbox is separate from the example presented above. A separate data point was set in the database and data (PeakVue and normal) acquired on a scheduled basis beginning on Mar. 16, 1998. One of the trend parameters captured for trending was the peak g-levels in the PeakVue time waveform. Experience has shown this to be a key parameter for fault detecting and severity assessment.

The PeakVue peak g-level trend parameter for the lower output shaft and PeakVue spectra for last collection date of May 28, 2000 are presented in Figure 4. The alert and fault levels are set at recommended levels for this speed machine and type fault. From the spectra, the fault is an inner race fault which is side banded (amplitude modulated) at running speed which is indicative of fault going in and out of load zone at running speed. From Figure 4, it is obvious that the fault exceeded the "fault" level about 7 months prior to replacement, in July 2000.

The trend value for bearing fault over the same time interval for the normal vibration monitoring are presented in Figure 5. Here there are no indications of a bearing fault.

Based on the trend values in PeakVue, a work order was release in June 2000 to replace the bearing. The bearing was replaced in July 2000. A picture of the defective bearing is presented in Figure 6. The failure was clearly advanced and could have induced catastrophic failure easily by e.g., metal "chunks" interfacing with the gear teeth meshing.

3.4 Cracked teeth in a Precision Tension Bridle Gearbox: This gearbox was a single speed reduction gearbox with a dual shaft output. The slow speed shaft from the reduction gear set (40 teeth pinion gear driving a 158 teeth bull gear) was driving a second output shaft through a dual 90 tooth gear set. The input shaft was turning at 525 rpm and the output shafts turning at 215 RPM at the time the data presented below was acquired.

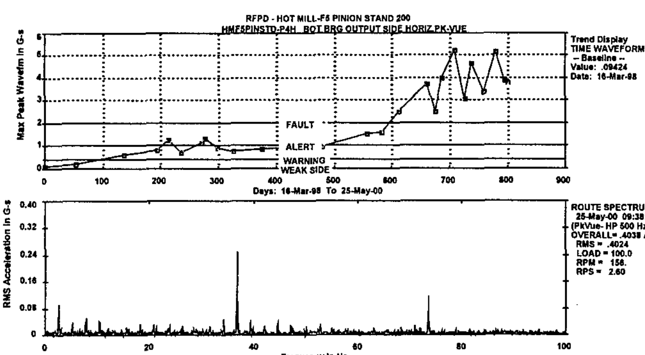

Figure 4. Maximum peak g-level (from PeakVue) trend from March 16, 1998 to May 25, 2000 and PeakVue spectra from May 25, 2000.

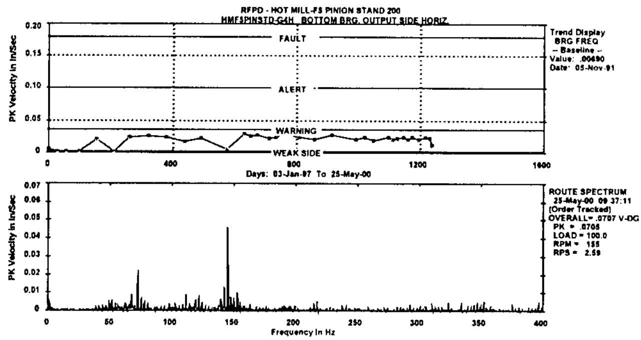

Figure 5. Normal vibration bearing fault trend and spectra for latest measurement over same time period as in Fig. 4.

Figure 6. Defective bearing taken from the pinion stand gearbox of Figs. 4 and 5.

The only accessible point for acquiring data was over the input shaft. The normal velocity vibration spectra and acceleration time waveform acquired on April 14, 1997 are presented in Figure 7. The speed reduction (input) gear mesh, 351 Hz, is dominant in the spectral data in Figure 7 and showing significant side banding (especially at 2 × GM). This pattern is indicative of gear wear and perhaps some misalignments. The P-P acceleration data in time waveform was less than 4 g's and not considered significant. This possible gear wear misalignment had been flagged with an action item to initiate a visual inspection at next opportunity.

It was decided to apply the PeakVue methodology on April 14, 1997. The PeakVue spectral and waveform data are presented in Figure 8. The only activity in the spectral data is the output shaft turning speed with many harmonics. The time waveform has two impacting regions per turn of the output shaft. The impacting levels exceed 40 g's. This signature indicates a gear with significant cracked teeth (at root) in two regions. One of the output shafts has the bull gear with 158 teeth and the pinion gear with 90 teeth driving

the second output shaft. The bandwidth in Figure 8 is not sufficient to encompass either gear mesh; therefore we cannot identify from this data set which gear set has the defective gear.*

From the spectral presented in Figure 7, one would be suspicious that the defective gear would be in the GM 1 set since nothing unusual is present relative to the GM 2 set. There was an additional PeakVue spectra taken with a bandwidth of 5000 Hz. In this PeakVue spectra set, the GM 2 activity was present and the GM 1 absent. This leads to the conclusion that the gears with the cracked teeth were most probably in the GM 2 set.

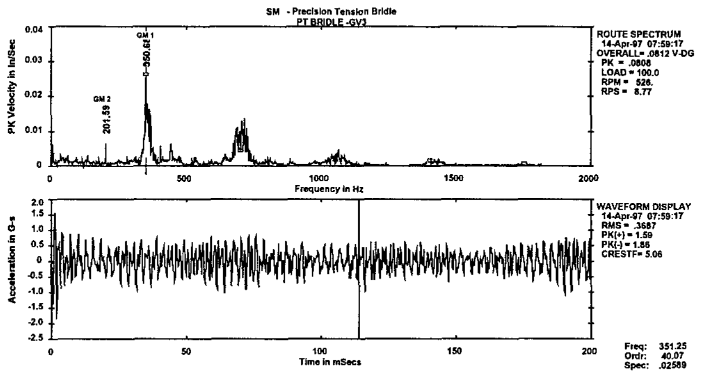

Figure 7. Velocity spectra and acceleration time wave form from the precision tension bridle gearbox.

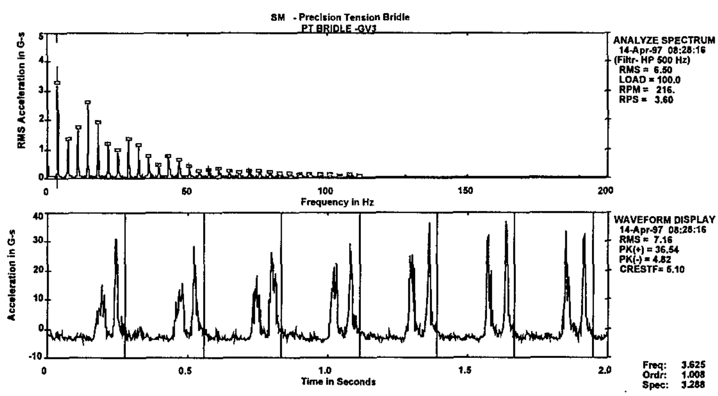

Figure 8. PeakVue spectra and time waveform from the precision tension bridle gearbox.

*The gear mesh where the defective gear is located would be present in the PeakVue spectra.

Following the acquisition of the PeakVue data, the gearbox was shortly shutdown and inspected. One of the gears in the GM 2 set was found to have two visible cracks.

3.5 Extruder Gearbox: The plan view of the extruder gearbox is presented in Figure 9. For the indicated input speed of 1840 RPM, the output shafts are turning at 316 RPM. The gear mesh frequencies are 1318 Hz, 659 Hz, 237 Hz, and 79 Hz. For a gearbox of this complexity, experience has shown a measurement point should be located at each bearing.

The monitoring of the gearbox using normal vibration and PeakVue methodologies identified worn gear sets, probable gear misalignment, defective bearings, and excessive driver (DC Motor) speed variations. The signatures identifying the driver speed variation are presented below.

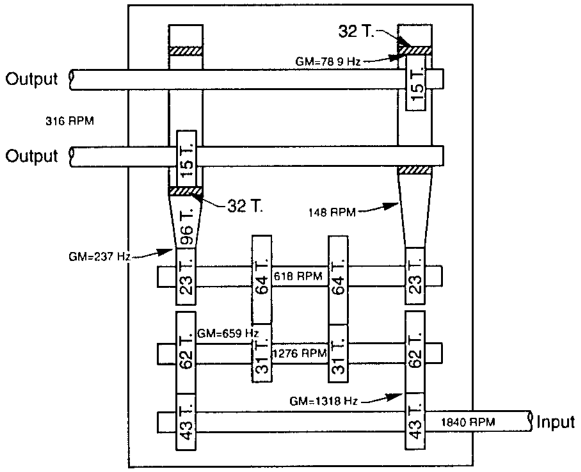

Figure 9. Plan view of the extruder gearbox.

The velocity spectra and acceleration time waveform for an input shaft speed of approximately 1825 RPM are presented in Figure 10. The dominant activity is the gear mesh for the 23T/96T set and the 43T/62T set. There are many harmonics of the 23T/96T set with the third being the largest (indicating looseness). The 43T/62T have reasonable shaft speed side banding at 2 × GM, which suggests some misalignment.

The PeakVue spectra and time waveform for inlet shaft speed of 1833 RPM are presented in Figure 11. There are activity at (1) the inlet shaft speed of 21.2 Hz (2) the first intermediate shaft speed at 31 Hz, and (3) the 43T/62T GM frequency and 2 times the 43T/62T GM frequency. The 2 times 43T/62T GM frequency is side banded with the shaft speed on which the bull gear is mounted. The impacting at 2 times gear mesh is indicative of significant back lashing which could be introduced with torsional resonance or (more probable) significant inlet shaft speed fluctuation.

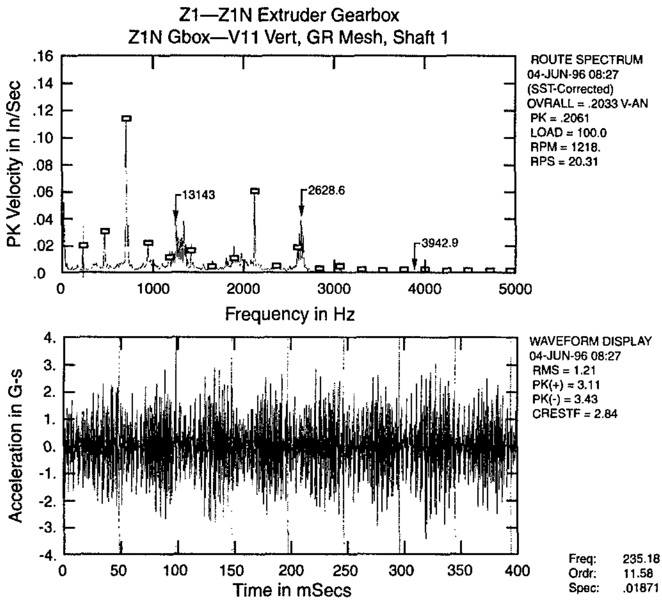

Figure 10. Velocity spectra and acceleration time waveform from extruder gearbox on June 4, 1996.

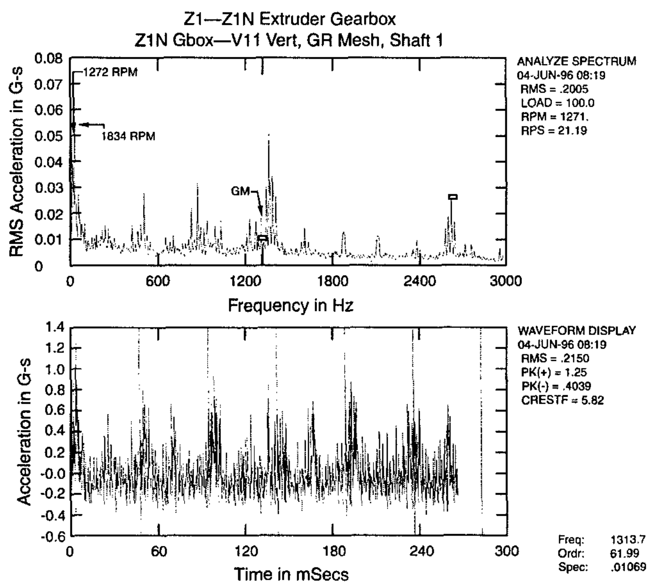

Figure 11. PeakVue spectra and time waveform form extruder gearbox on June 4, 1996.

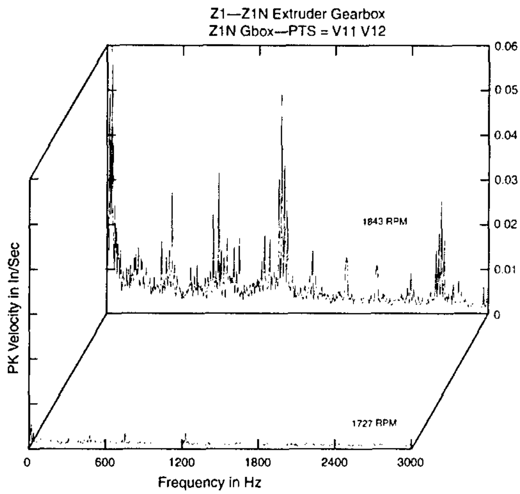

Figure 12. PeakVue spectra on extruder gearbox before DC motor speed adjustment (1843 RPM) and PeakVue spectra on extruder gearbox after DC motor speed adjustment (1727 RPM).

Spectra data on the inboard of the DC motor showed excessive* activity of 0.2 ips-peak at the SCR frequency (360 Hz) with amplitude variation (side banding) at the motor shaft frequency (inlet shaft to gearbox) and first intermediate shaft of the gearbox. The speed controller was adjusted and measurements on the gearbox repeated. The velocity spectra did not change, i.e., the 23T/96T set still showed signs of looseness and the 43T/62T set still showed probable misalignment. There were significant differences in the PeakVue spectra as shown in Figure 12. The spectra captured after adjustment of the speed controller (1727 RPM) shows no indication of impacting.

3.4 Crusher Gearbox: This gear box, driven by a 8-pole 2000 HP motor, drives a rock crusher at a mining facility. A plan view of the gearbox is presented in Figure 13. The gearbox is nominally 17′ × 12′ × 7′ in size. Normal vibration and PeakVue data was acquired on a scheduled basis on the motor and, as much as possible, at each bearing with the gearbox. The input shaft speed was in the proximity of 894 RPM. The first intermediate shaft was turning at 531.5 RPM or 8.86 Hz.

The PeakVue spectra and time waveform data taken at measurement point 3 (see Figure 13) are presented in Figure 14. The dominant activity in the PeakVue spectra are the intermediate shaft turning speed (8.86 Hz) and many harmonics with the 4^{th}, 8^{th}, 12^{th} etc. being dominant. In the PeakVue time waveform, Figure 14, there are four distinct impacts per turn of the first intermediate shaft (the vertical lines are spaced at time increments corresponding to the first intermediate shaft turning speed).

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*Vibration exceeding 0.1 ips-peak at the SCR firing frequency on inboard of a DC Motor generally imply a problem in the controller circuit.

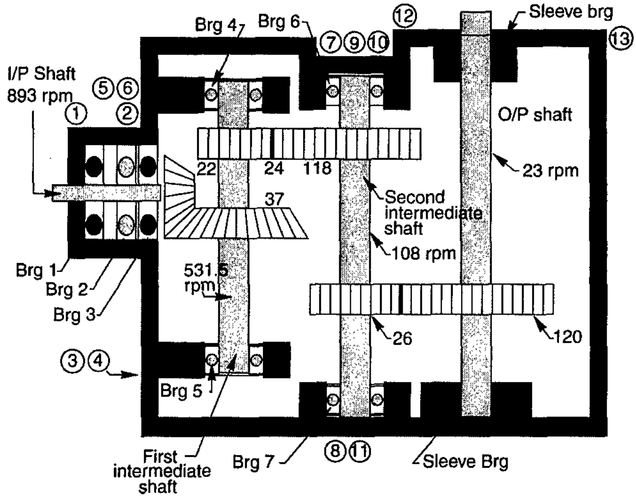

Figure 13. Plan view of crusher gearbox.

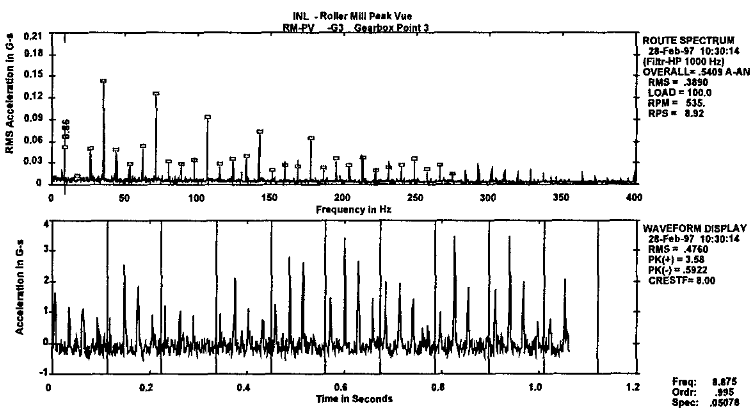

Figure 14. PeakVue spectra and time waveform taken on crusher gearbox at point 3.

The first intermediate shaft has a beveled bull gear with 37 T and a pinion gear with 22 T (see Figure 13). The first postulate was that the 24 T pinion gear had some fault at every 6th tooth since the total number of teeth (24) was divisible by 4. The bothersome fact with this postulate was the g levels of the impacts were greater at measurement point 3 than at measurement point 5 (the 24 T pinion was closer to measurement point 5). The impacts were clearly occurring at four equal intervals per rev of the first intermediate shaft and hence the 37 T bull gear was not considered to be the source where the impacting had occurred (37 not divisible by four).

The gearbox was disassembled and inspected. The 24 T pinion showed no indication of a problem. The impacting was occurring between the 37 T bull gear and the first intermediate shaft. An approximate 2 in. band of fretting was completely around the intermediate shaft at the top of the beveled bull gear.

The postulate then was the impacting was being introduced by a reasonable sharp (high Q) torsional resonance of the input shaft. Strain gauges were installed near the gearbox on the inlet shaft and torsional vibrations data acquired. The torsional resonance spectra showed dominant activity at 35.3 Hz, which is 4 times the intermediate shaft speed.

4. Conclusions: The capture and analysis of stress waves, which accompany many classes of faults experienced in gearboxes, has proven to be an effective diagnostic tool for fault detection and severity assessment in gearboxes. In this paper, five typical examples of faults within gearboxes were presented as case studies. In each case, the normal vibration analysis contributed very little to the fault detection and severity assessment.

The PeakVue methodology for the capture and analysis of the stress waves provide a very powerful trending capability. This is the case since the true amplitude of the specific faults in g-units is captured independent of the machine speed, the analysis bandwidth etc. This ability to capture the true impacting levels provides the knowledge to develop absolute levels from which alert levels and alarms can be set based on a broad case history library. Experience has shown these levels to be dependent on machine speed (in a predictable manner) and fault type (the same as in normal vibration analysis).